The author’s respond to the Reviewer #1

Reviewer #1. Recommendation:
The paper should be published after taking into account this deficiency.

Reviewer‘s comments

Note, that the circulation of the Japan Sea was an object of study by many authors for a long time. In my opinion, this study lacked a comparison with the schemes of currents obtained, for example, in

• *Chang, K.-I., Teague, S.J., Lyu, S. J., Perkins, H. T., Lee, D.-K., Watts, D. R., Kim, Y.-B., Mitchell, D.A., Lee, C.M., and Kim, K. Circulation and currents in the southwestern East/Japan Sea: Overview and review. Progr. Oceanogr., 61, 105-156, doi:10.1016/j.pocean.2004.06.005, 2004.*

• *Holloway, G., Soul, T., and Eby, M. Dynamics of circulation of the Japan Sea. J. Mar. Res., 53, 539-569, doi:10.1357/0022240953213106, 1995.*

• *Kawabe, M. Branching of the Tshushima Current in the Japan Sea. Part I. Data analysis. J. Oceaonogr. Soc. Japan, 38, 95-107, doi:10.1007/BF02110295, 1982.*

• *Kawabe, M. Branching of the Tshushima Current in the Japan Sea. Part II. Numerical experiment. J. Oceaonogr. Soc. Japan, 38, 183-192, doi:10.1007/BF02111101, 1982.*

• *Sekine, Y. Wind-driven circulation in the Japan Sea and its influence on the branching of the Tsushima Current. Progr. Oceanogr., 17, 297-313, doi:10.1016/0079-6611(86)90051-0, 1986.*

• *Senjyu, T. The Japan Sea intermediate water; its characteristics and circulation. J. Oceanogr. 55, 111-122, doi:10.1023/A:1007825609622, 1999.*

• *Takano, K., ed. 1991. Oceanography of Asian Marginal Seas, Elsevier, 431 pp.*

• *Yoon, J. H. Numerical experiment on the circulation in the Japan Sea. Part I: Formation of the East Korea Warm Current. J. Oceanogr. Soc. Japan, 38, 43-51, doi:10.1007/BF02110289, 1982.*

• *Yoon, J. H. Numerical experiment on the circulation in the Japan Sea. Part II: Influence of seasonal variations in atmospheric conditions on the Tsushima Current. J. Oceanogr. Soc. Japan, 38, 81-94, doi: 10.1007/BF02110294, 1982.*

• *Yoon, J. H. Numerical experiment on the circulation in the Japan Sea. Part III: Formation of the nearshore branch of the Tsushima Current. J. Oceanogr. Soc. Japan, 38, 125-130, doi:10.1007/BF02110283, 1982.* • *You, Y., Chang, K.-I., Yun, J.-Y., and Kim, K.-R. Thermocline circulation and ventilation of the East/Japan Sea, part I: Water-mass characteristics and transports. Deep Sea Res. Part II: Topical Studies in Oceanography, 57, 1221–1246, doi:10.1016/j.dsr2.2009.12.011, 2010.*

Our respond

We thank the Reviewer for providing us the above mentioned references. We compared briefly in the revised text our averaged AVISO velocity field and its main large-scale features, including persistent mesoscale eddies in the basin, with the schemes of the Japan Sea (JS) surface circulation obtained in the references proposed by the Reviewer. We referred to most of those references in Introduction and in the first paragraph in Sec.3.1 in addition to already referred papers on this subject. However, the main intent of our ms was not a review of currents in the JS and their variability but a Lagrangian statistical analysis of near-surface transport of subtropical waters in the JS frontal area.

The author’s respond to the Reviewer #2

Reviewer #2. Recommendation:
The paper merits for publication in NPG, however some minor changes should be done that in my opinion may enrich the text.

1. Cited from the referee's report

Colors or gray shades in Fig.2 should be different as it is impossible to see anything. I do not understand why to compare with real drifters in Fig.3. Drifters and tracers do not match as it is already stated by the authors. The corresponding blue line should be deleted from Fig.3. Vertical black lines in Fig.3 confuse the reader.

Our response

As to Fig.2, it does not pretend to give an exact quantitative information. It designed to show a meridional inhomogeneity of northward transport of subtropical water across the Subpolar Front with an increased (decreased) density of points corresponding to transport gates and barriers, respectively. It is clear that areas with increased density of points in Fig. 2a correlate well with areas with increased average values of the northward component of the AVISO velocity field in Fig. 2b. The chosen color gradation has been found empirically to be optimal to represent forbidden zones as bright spots. We would like to stress that the density difference in some meridional ranges in Fig. 2a may be very large because of the logarithmic-scale representation.

As to Fig.3, the meridional dependence of the number of crossings of zonal lines by available drifters confirms partly the existence of simulated forbidden zones. The vertical black lines in Fig.3 are plotted to compare different curves and their maxima and minima.

We rewritten the first two paragraphs in Sec.3.2 to be: "Now let's look more carefully at the meridional distribution of subtropical tracers crossed the Subpolar Front for the whole period of simulation. We choose for reference four zonal lines along the AVISO grid at \N{42.125}, \N{41.875}, \N{40.125} and \N{39.875}. They are shown in Fig.~\ref{fig3} by solid curves with superimposed meridional distributions of the averaged northward AVISO velocity (arrows). The number of crossings of those latitudes by available 333 drifters is shown by dashed curves.

The correspondence between the peaks in the meridional distributions of the tracers, drifters and the averaged northward AVISO velocity is rather good for all the chosen zonal lines confirming their direct connection. However, the comparison with drifters should be taken with care because of a comparatively small number of available drifters. Drifters, are not ideal passive tracers, and their motion is subjected to submesoscale features which were not caught by altimetry-derived data. Moreover, the drifters have not been launched at the zonal line \N{37} like artificial tracers in simulation. Their launch sites for more than 20 years have been distributed rather randomly over the basin."

The correspondence between the curves for drifters and the averaged northward component of the AVISO velocity is rather good at 40 N. It is worse at 42 N, however, it is clear that the drifters are transported mainly by the Tsushima Current. The vertical black lines in Fig.3 facilitate a comparison between different curves.

2. Cited from the referee's report

Why do you choose so strange latitudes as 39.875, 40.125, etc in Fig.3 when in the rest of the paper, latitudes are integer numbers as 40N or 42N? Could you re-draw that Figure to be consistent?

Our response

In Fig.3 they are chosen to fit the AVISO grid where we estimate the AVISO velocities. We need not that in other figures.

3. Cited from the referee's report

Besides, Fig.4 is quite obscure, and the results shown there are already shown in Fig.3. Why do not define the regions (I to VIII) in Fig.3? Clearly, due to the coast line and currents most of the particles should move towards the east as they move northward as it is already shown in Fig.3 and repeated in Fig.4. In my opinion Fig.4 could be deleted.

Our response

Figure 4 contains new information as compared to Fig.3. It shows how many and at which final longitudes λ_f the tracers with initial longitudes λ_0, launched weekly at t 37N from

January 2, 1993 to June 15, 2013, were able to cross 40N and 42N latitudes. The three paragraphs in Sec.3.2 are devoted to describe this new information.

4. Cited from the referee's report

An interesting result shown in Fig.5 is that gates may be closed during some period of time (white patches at certain longitudes). However the reason for that it is not clear for me. May be the authors should make an effort to explain that more clearly. These patches repeat regularly on time? may be with a seasonal period?

Our response

It is defined by the properties of the local advective velocity field. The gates open due to suitable dispositions of mesoscale frontal eddies facilitating propagation of subtropical waters to the north. It is documented in the paper with the help of different kinds of Lagrangian maps in Figs.6 and 7 and validated by tracks of available drifters. For example, a vortex street with four anticyclones has been formed in the fall of 2005 to the north of the Subpolar Front in the western part of the sea. Their centers are marked in Fig. 6a by the elliptic points (triangles) with the coordinates 39.1N, 131.5 E; 39.3N, 130.1E; 40.8N, 131.4E and 41.7N,130.8E. It is explained on p.11 (L.10-15), on p.12 (L.80-15) and on p.11 (L.10-15) in the text. The gates open at those places where suitable dispositions of eddies and vortex streets appear time to time to facilitate the northward transport. They may appear due to different reasons, e.g., due to a seasonal variability of the current field, migration of frontal eddies, etc.

5. Cited from the referee's report

Finally, the English style should be checked, but I suppose the journal will take care of that later on.

Our response

We did our best to edit all the text.

The author's respond to the Reviewer #3

We are very grateful to the Referee for a very careful reading of the manuscript and a number of useful comments and critics we tried to take into account in the revised version.

III. Reviewer #3: Recommendation -

In general, the authors present a interesting work aimed at improving the description of surface transport in the Japan Sea in terms of Lagrangian statistic indicators. This is a good piece of work which can be of interest to some NPG readers. However a minor/major revision has to be addressed before publication. The main issues that need to be clarified by the authors are listed bellow.

Responses to the Third Reviewer's report
Major concerns:
GENERAL REMARKS:
1. Cited from the referee's report

1. Although the study has relevant results to understand the mesoscale transport dynamics at the surface of the Japan Sea, I found that some of the results are repeated throughout the manuscript, becoming redundant. For instance the information that can be obtained from Figure 4 can be deduced from the other figures.

Our response

Figure 4 shows how many and at which final longitudes λ_f the tracers with initial longitudes λ_0, launched weekly at 37N from January 2, 1993 to June 15, 2013, were able to cross 40N and 42N latitudes. The three paragraphs in Sec.3.2 are devoted to describe this new information. This information is absent in other figures in the paper.

2. Cited from the referee's report

2. Also it's really hard to follow the storyline of the study, I have found many unnecessary repetitions of descriptions and a lot of sentence and expressions that do not make sense. The manuscript needs a careful read through. A copy editing of the text would be highly appreciated to make the reading easier.

Our response

We did our best to improve the English, to edit the paper, to remove repetitions and to clarify the sentences and expressions indicated by the referee.

3. Cited from the referee's report

3. The authors analyze how is the northward transport in relation to zonal fronts located at the middle of the basin of the Japan Sea near 40 N. However looking at Figure 1 one can see that these fronts extends from 37N to 42 N. In fact the authors only analyze the flux of particles at latitudes from 39.875 to 42.125 (Figure 3). Please could you clarify this choice?

Our response

Our aim was to analyze northward transport not over all the Japan Sea but across the subpolar frontal zone between 40N and 42N only**.**

4. Cited from the referee's report

4. Have the authors compared the intrusions of subtropical waters (figure 6) with Sea Surface Temperature or Ocean color satellite images? It could help you to prove with observations such dynamical features?

Our response

No.

Abstract:

5. Cited from the referee's report

1. The authors repeat several times "Lagrangian indicators (line 2)", Lagrangian maps (line 7) without specifying the Lagrangian diagnosis used in the study.

Our response

The text, describing Lagrangian indicators and maps, has been added to Sec.2 as follows:

"Each water parcel can be attributed to temperature, salinity, density and other properties which characterize this volume as it moves. In addition, each water parcel can be attributed to more specific characteristics which are trajectory's functions called ``Lagrangian indicators''. They are, for example, a distance passed by a fluid particle, its displacement from an original position, time of residence of fluid particles inside a given area and others. The Lagrangian indicators contain information about the origin, history and fate of the corresponding water masses. Lagrangian maps are plots of Lagrangian indicators versus particle's initial positions. A studied area is seeded with a large number of tracers whose trajectories are computed for a given period of time to get the field of a specific Lagrangian indicator in this area. Finally, its values are coded by color and represented as a map in geographic coordinates."

6. Cited from the referee's report

3. Sentence in lines 5-6. It is hard to understand how the eddies open the gates due to their suitable dispositions. What does "suitable dispositions" means?

Our response

We mean by a suitable disposition of mesoscale eddies such a configuration where one of the eddies gains an amount of subtropical water from the south, wraps it around and transports that water to the north where another eddy is appropriately situated to do the same. This situation is documented in the paper with the help of different kinds of Lagrangian maps in Figs.6 and 7 and validated by tracks of available drifters. For example, a vortex street with four anticyclones has been formed in the fall of 2005 to the north of the Subpolar Front in the western part of the sea. Their centers are marked in Fig. 6a by the elliptic points (triangles) with the coordinates 39.1N, 131.5 E; 39.3N, 130.1E; 40.8N, 131.4E and 41.7N,130.8E. It is explained on p.11 (L.10-25), on p.11 (L.26-33) and on p.12 (L.11-18) in the text. The gates open at those places where suitable dispositions of eddies and vortex streets appear time to time to facilitate the northward transport. They may appear due to different reasons, e.g., due to a seasonal variability of the current field, migration of frontal eddies etc.

7. Cited from the referee's report

2. Last two sentences: It's clear that something is happening because of the peculiarities of the advection velocity field, but which one? Please be more precise.

Our response

These peculiarities of the advective velocity field are described in detail in the last paragraph in Sec.3.1.

Introduction:

8. Cited from the referee's report

1. Figure 1 shows high values of northeastward velocity data in the TS (Tsugaru strait)? It means that, in average, the most of particles escape throughout this strait to the Pacific Ocean? Do the authors know if there is a realtionship between these features with the frontal-pair-vortex systems (AC-C) located at the entrance of the strait?

Our response

The high velocity in the strait does not mean that all the particles escape throughout this strait to the Pacific Ocean because it is compensated by a narrowness of the strait. We did not estimate the number of particles escaping to the Pacific Ocean and a connection of the AC-C vortex pair to that escape.

9. Cited from the referee's report

2. Please move to the first paragraph (where you are describing the bathymetry) the sentence in line 19 (page 1) with the reference to the figure showing the bathymetry.

Our response

Done.

10. Cited from the referee's report

3. Acronyms: The text is full of acronyms. - Could the authors explain what does SF mean (line 5, page 2)? Salinity fronts? - It could be great if the authors describe all the acronyms in the introductory part (second paragragh of introduction section) and not in the Results section (first paragraph of section 3.1) neither in the caption of Figure 1.

Our response

SF means a Subpolar front, but we removed that acronym from the revised text. We left in the main text only JS for the Japan Sea and AC and C for anticyclones and cyclones. The other acronyms in the text refer to the corresponding figures.

Data and methods:

11. Cited from the referee's report

1. The time step used for the Runge-Kutta integration is 1/1000. It means 0.001 days (1.5 minutes)? Why this such short time step? Have you compared the results using a longer time step, namely, 1 day (the time resolution of the Altimetry data?)

Our response

This time step is optimal to integrate ODEs. A 1 day step implies much more large numerical errors.

12. Cited from the referee's report

2. It is hard to understand the sentences from line 18 and line 21 page 4: " Trajectory of each : : :........in the northward transport only." Authors say that "the fixed the position and time of each tracers when they cross a given latitude between 37 and 43" and then they say that they "fix only the first crossing of a given latitude". Could the authors clarify this part of the methodology?

Our response

Some tracers could cross a few times the same zonal line in the northward direction. For example, if they belong to an eddy crossing that line. We fix only the first crossing of a given latitude by tracers.

13. Cited from the referee's report

3. line 21 page 4. Could the authors explain how a cell of AVISO can have two corners situated at land? As far as I am concerned a cell of AVISO only can be either land or ocean depending of the land mask. Maybe they mean two corners of the integration cell situated at land?

Our response

The AVISO grid contains points which are either at the land or in the sea. We mean by the cell a rectangle with 4 corners. There is no integration cells in integrating ODEs.

14. Cited from the referee's report

4. line 23-25. Could the authors read carefully and rewrite the paragraph? The sentence does not make sense.

Our response

It is rewritten to be "To simulate and analyze transport across the frontal area, we solve successively a few tasks which are numbered in the text in accordance with the following diagrams and Lagrangian maps."

15. Cited from the referee's report

5. Could the authors provide a description of the methodology used to compute and classify the fixed points of the velocity field in elliptic and hyperbolic points? The velocity field in the centers of the eddies is different to zero. Could the streamlines of saddle nodes be used to localize fronts?

Our response

The stagnation points are zeroes of the interpolated velocity field at a fixed moment of time. They could be distinguished by eigenvalues of the evolution matrix. A point with zero velocity always exists at the eddy's center in a steady velocity field. The streamlines of saddle nodes could be really used to localize fronts but approximately only, because it's not obligatory for a real front to pass through an instantaneous hyperbolic point.

16. Cited from the referee's report

6. Please specify the number of drifters used in the study?

Our response

The number of drifters used in the study was 333. It has been added to the text.

Results and Discussion

17. Cited from the referee's report

1. The description given in the first paragraph is already provided in the introductory part

(line 31 page 3 and lines 1, 2 page 4).

Our response

The first paragraph has been deleted and the second one was removed to Introduction.

18. Cited from the referee's report

2. First and second paragraph of this section are not results and they should be in the Introduction or in the Data and methods sections.

Our response

The first paragraph has been deleted and the second one was removed to Introduction.

19. Cited from the referee's report

3. Second paragraph page 7. Eulerian (time average of northward velocities, Fig. 2b) with Lagrangian (particles trajectories crossing different latitudes, Fig. 2a) diagnosis are compared. Authors state that both diagnosis are equivalent because the transport is determined by local advection. It means that the dynamics is controlled by the local scales ("small scales") and not by the large scales?

Our response

In the Lagrangian approach the dynamics is always local because it is governed by advection equations (1). The local advective velocity field determines where fluid particles cross a given latitude. However, the relative number of such crossings in different meridional peaks in Fig.2 is defined by a large-scale dynamics and initial conditions.

20. Cited from the referee's report

4. Do Fig. 3 show zonal cross-sections of Fig. 2 for four latitudes? If so, why the authors do not relate both figures in the manuscript, it could help to the reader. I do not know what does means "central part"? Authors state that "the correlation is rather good for western and eastern parts but not for the central one" (line 31-32, page 7), however, I see a good correlation between virtual and real drifters in the central part of the Japan Sea (see minima in Fig. 3 at 134E-136E). Moreover, this correlation is stronger in the north part (higher latitudes) than in the southern. Maybe because of the number of available drifters? Could the authors specify the number of drifters? Have the authors values of the correlations coefficients?

Our response

Yes, Fig.3 is a zonal cross sections of Fig. 2 for four latitudes.

The first two paragraphs in Sec.3.2 have been rewritten to be: "Now let's look more carefully at the meridional distribution of subtropical tracers crossed the Subpolar Front for the whole period of simulation. We choose for reference four zonal lines along the AVISO grid at \N{42.125}, \N{41.875}, \N{40.125} and \N{39.875}. They are shown in Fig.~\ref{fig3} by solid curves with superimposed meridional distributions of the averaged northward AVISO velocity (arrows). The number of crossings of those latitudes by available 333 drifters is shown by dashed curves. The correspondence between the peaks in the meridional distributions of the tracers, drifters and the averaged northward AVISO velocity is rather good for all the chosen zonal lines confirming their direct connection. However, the comparison with drifters should be taken with care because of a comparatively small number of available drifters. Drifters, are not ideal passive tracers, and their motion is subjected to submesoscale features which were not caught by altimetry-derived data. Moreover, the drifters have not been launched at the zonal line \N{37} like artificial tracers in simulation. Their launch sites for more than 20 years have been distributed rather randomly over the basin."

21. Cited from the referee's report

5. With regard to the bad correlation with drifters (line 32-33 page 7), other explanation could be because drifters movement is due also to submesoscale features which are not provided by velocities derived from altimetry.

Our response

We corrected the corresponding sentences as indicated above.

22. Cited from the referee's report

6. Line 2 page 8. How does the authors know that drifters have been launched randomly over the basin? Could they provide references on these drifters experiments explaining these random releases?

Our response

333 drifters have been launched for 20 years at different places. For our purposes, their releases could be considered to be random. As to references on these drifters experiments, it would take too much place in the Reference list and has no direct relation to our study.

23. Cited from the referee's report

6. Drifters are not launched at 37 N but at least they have to cross this latitude to take them into account in the meridional transport computations.

Our response

It is hardly possible to compare drifter's tracks with tracks of individual synthetic tracers in the AVISO velocity field by the reasons mentioned in the respond No.20. We use available drifters in order to demonstrate that they, like synthetic tracers, prefer to cross given latitudes at specific places (gates).

24. Cited from the referee's report

7. Second paragraph is confused. I do not know how to differentiate gates and barriers from Fig 3. Minima and maxima of numbers of tracers?. Could the authors clarify this point?

Our response

Yes, local maxima and minima of the number of tracers correspond to gates and barriers, respectively. It is clarified in the revised text as follows "The local maxima and minima of the distribution function correspond to gates and conditional barriers, respectively."

25. Cited from the referee's report

8. It is difficult to deduce from Figure 4 the parameter chosen by the authors to define the size of gates and barriers.

Our response

The size of the gates in Fig.4 is defined by the minima of the distribution function $N(\lambda_f)$ at the latitude 42N.

26. Cited from the referee's report

9. Line 1-2, page 11. It's hard to understand what the authors mean in this sentence.

Our response

That's our statement mentioned by the referee: "Thus, the northward transport of subtropical water across the Subpolar Front occurs by a portion-like manner. Specific oceanographic conditions may arise in a given area and at a given time which produce a large-scale intrusion of subtropical water to the north by means of mesoscale eddies to be present there."

It is described just above that sentence in the text why it occurs by a portion-like manner. By specific oceanographic conditions providing a large-scale intrusion of subtropical water to the north, we mean mainly suitable dispositions of frontal mesoscale eddies. This point was clarified in our respond No.6 and in the corresponding place in the text.

27. Cited from the referee's report

10. Line 3, page 11- This motivation has been included in the introductory sections. Please avoid repetitions.

Our response

OK, we deleted that.

28. Cited from the referee’s report

11. Line 6, page 11. Definition of Lagrangian Maps is not clear: I really do suggest that the authors rewrite it.

Our response

The following text, describing Lagrangian indicators and maps, has been added to Sec.2: “Each water parcel can be attributed to temperature, salinity, density and other properties which characterize this volume as it moves. In addition, each water parcel can be attributed to more specific characteristics which are trajectory's functions called ``Lagrangian indicators''. They are, for example, a distance passed by a fluid particle, its displacement from an original position, its travel time and others. The Lagrangian indicators contain information about the origin, history and fate of the corresponding water masses. Lagrangian maps are plots of Lagrangian indicators versus particle's initial positions. A studied area is seeded with a large number of tracers whose trajectories
are computed for a given period of time to get the field of a specific Lagrangian indicator whose values are coded by color and represented as a map in geographic coordinates.”

29. Cited from the referee’s report

12. Fig 6 correspond to maps of residence times computed backward in time. They are the incoming times and it has been already used for several authors:
- Lipphardt, B., Jr., Small, D., Kirwan, A., Jr., Wiggins, S., Ide, K., Grosch, C., and Paduan, J.: Synoptic Lagrangian maps: Aplication to surface transport in Monterey Bay, J. Mar. Res., 64, 221– 247, 2006.
- H. Gildor, E. Fredj, J. Steinbuck, S. Monismith. Evidence for submesoscale barriers to horizontal mixing in the ocean from current measurements and aerial photographs. Journal of Physical Oceanography, 39, 1975–1983, 2009.
- Hernбndez-Carrasco, I., Lypez,C., Orfila, A., and Hernбndez-Garcнa, E.; Lagrangian transport in a microtidal coastal area: the Bay of Palma, island of Mallorca, Spain. Nonlin. Processes Geophys., 20, 921–933, 2013.

Our response

Formally, Fig 6 is not a map of residence times. It is a map of travelling time T that took for subtropical tracers to reach to a specific date their locations on the map from the latitude 37N. We have added the first and third references to the text. The second one has no relation to the residence maps.

30. Cited from the referee’s report

13. It could be great if authors include a reference when they say that Peripheries of the mesoscale eddies in the ocean are known to be transport pathways for larvae, fish : : :..... (lines 5-6, page 12).

Our response

There is a vast literature on that subject. We have referred to some in the revised text (see, e.g., Cotte2010,P13,Prants2014c and references therein).

31. Cited from the referee’s report

14. Sentence in line 7: “: : :..kind of transport for heat-loving organisms to reach the southern coast of Russia”. It means that the coast of Russia is warm?

Our response

It means that some subtropical (=heat-loving) organisms are able to reach the southern coast of Russia. Most of people are rather heat-loving organisms, but they could reach the Earth’s poles using some transport means.

32. Cited from the referee’s report

15. The paragraph (lines 8-15) could be improved if the authors reorganize the text. Lines 11-13 (“ The red and green : : :....respectively”) could be move in before line 10 (“In the beginning of September : : :...pulled to the north.”)

Our response

Done.

33. Cited from the referee’s report

16. Line 3, page 13. It seems that this is the mechanism to explain the intrusions of subtropical waters (Figure 6). The manuscript could be improved if authors are more explicits.

Our response

We clarified in our respond No.6 how frontal eddies could facilitate the northward transport of subtropical water. It is also described in Sec.3.2 for the western, central and eastern gates and in the Supplementary material.

34. Cited from the referee’s report

17. Is the displacements of the tracers (D) a Lagrangian diagnosis developed by other authors, by means of the function M, in order to obtain the Lagrangian Coherent Structures?:
- Mendoza, C. and Mancho, A. M.: The hidden geometry of ocean flows, Phys. Rev. Lett., 105, 038501, doi:10.1103/PhysRevLett.105.038501, 2010.

Our response

The definition of particle’s displacement D has been added to Sec.2 as follows”:
The drift maps show by nuances of the grey color the finite-time displacement of tracers, D, that is a distance between final, $(\lambda_f,\,\varphi_f)$, and initial, $(\lambda_0,\,\varphi_0)$, positions of advected particles on the Earth sphere with the radius R_E
\begin{equation}
D\equiv R_E\arccos[\sin \varphi_0 \sin \varphi_f +\cos \varphi_0 \cos \varphi_f
\cos (\lambda_f - \lambda_0)].
\label{drift}
\end{equation}
It is not the length of a trajectory.

35. Cited from the referee’s report

18. Line 7, page 13. “ so, the black tracers : : :......white ones” I do not understand what the authors mean with “displaced”. What is the difference between white and black colors? The length of the trajectory?

Our response

See please the preceding respond. The black particles have displaced for an integration time much farther that the white ones.

36. Cited from the referee’s report

19. Line 14, page 13: “....pro-pulsed to the northwest”. Do the authors mean “northeast” instead of “northwest”? It seems that particles are not transported northwestward by the frontal-pair-vortex system but northeastward.

Our response

Corrected. Thank you.

37. Cited from the referee’s report

20. I do not understand the last paragraph from line 14 to line 18, page 13. Are the authors describing the drifter trajectories?

Our response

Yes, we describe the drifter’s track shown by green circles in Fig.7.

38. Cited from the referee’s report

21. Line 24: Simulations with “imperfect” AVISO is compared with satellite, drifter and in situ observations. What kind of satellite product has been used to be compared with AVISO? When comparing with drifter trajectories you should take into account that drifter velocities has to be different than the geostrophic velocities derived from AVISO by definition.

Our response

We removed all that paragraph.

39. Cited from the referee’s report

22. Line 25-30. This sentence has been mentioned three times in the manuscript. Please avoid repetitions.

Our response

We removed all that paragraph.

40. Cited from the referee’s report

23. Line 31: “Nobody knows, of course true velocity field in the real ocean” This sentence is not necessary, please remove it.

Our response

Removed.

41. Cited from the referee’s report

24. Line 32: “The AVISO velocity field has errors as compared with an unknown “true” velocity field...”. This sentence is not logical: in my opinion anything can not be compared with things that are unknown, because they are unknown. One could say that the unknown part of the velocity field could be simulated by adding noise in the velocity data.

Our response

Corrected to be: “The AVISO velocity field has errors as compared with a ``true" velocity field. The difference could be simulated by adding a noise $\Delta (u,v)$ in the velocity data.”

42. Cited from the referee’s report

25. Line 34, page 13. What does “To which extent one can trust to them” mean?

Our response

This sentence was removed.

43. Cited from the referee’s report

26. Line 19, page 4. This study of adding errors in the velocity field to compute the trajectories has been performed for the FTLE and also for FSLE.

Our response

Corrected to be “…by the finite-time and finite-size Lyapunov techniques.”

Conclusions

44. Cited from the referee’s report

1. I have found many repetitions that have been copied from the body of the manuscript. I suggest that the authors rewrite the whole conclusions section.

Our response

We removed all the not necessary repetitions in the revised version.

45. Cited from the referee’s report

2. Please remove references to the Figures.

Our response

It seems to us that it would be more convenient to the reader to get a reference to the figure which illustrates the corresponding result.

Technical comments:

46. Cited from the referee's report

1. Please remove "there" (last word of abstract, line 11, page 1)

Our response

Oк

47. Cited from the referee's report

2. Why "Sea" (line 5 page 2) is in capital letter?

Our response

Corrected.

48. Cited from the referee's report

3. Line 6 page: 3 replace "to the coast" with "in the coast"

Our response

Corrected.

49. Cited from the referee's report

4. Line 10, page 3: Remove "across it".

Our response

Corrected.

50. Cited from the referee's report

5. Line 11 page 3: in " we use the altimetry data" remove "the".

Our response

Corrected.

51. Cited from the referee's report

6. Line 14 page 3. Remove "based on altimetry data". It has already been stated several times in the text. Please avoid repetitions.

Our response

Done.

52. Cited from the referee's report

7. Line 25, 26, page 7, It is not necessary to specify the longitudes for the zonal cross-section but only with the latitude the reader can localize the zonal lines.

Our response

Corrected.

53. Cited from the referee's report

8. Please read carefully the lines 28 in page 7 and rewrite the text: " The number of crossing : : :....dashed curves" by for instance "The number of available drifters crossing the given latitudes are shown : : :......".

Our response

Corrected to be: The number of crossings of those latitudes by available 333 drifters is shown by dashed curves.

54. Cited from the referee's report

9. There are many "to the" through the manuscript that should be replaced with "at the" or "in the"

Our response

Done.

55. Cited from the referee's report

10. Line 1 , page 9. What does "task 2" mean? Authors use "task X" throughout the manuscript to refer to the computations given in the Data and methods section. It could be great if it is stated in the methodology section that the computation X correspond to task X. (Although task is usually used in the context of a project and not in a paper).

Our response

It is clarified in Sec.2 as follows: "To simulate and analyze transport across the frontal area, we solve successively a few tasks which are numbered in the text in accordance with the following diagrams and Lagrangian maps."

56. Cited from the referee's report

11. There are two reference for Prants et al, 2015.

Our response

There are no two references for Prants et al, 2015.

57. Cited from the referee's report

12. Line 1, page 12. Please remove the website of drifter data (it has been shown in Data and Methods) and also the number of the drifters.

Our response

Done.

58. Cited from the referee's report

13. Line 23, page 13. Remove "the" before AVISO and "we used" after AVISO.

Our response

Done.

59. Cited from the referee's report

14. Line 5, page 14. Please replace the sentence " So , locations of the preferred : : :...are possible" with "So, locations of the preferred transport pathways are not expected to be changed significantly".

Our response

Corrected.

60. Cited from the referee's report

15. Line 9, page 14. Please replace "Say" with "For example".

Our response

Done.

61. Cited from the referee's report

16. Line 14, page 14. Replace "a plenty of " by "the presence of numerous".

Our response

Done.

62. Cited from the referee's report

17. Line 16, page 14. Replace "As to" by "The" and remove "it"

Our response

Done.

63. Cited from the referee's report

18. Line 17, page 14. Add "by analyzing" just before "how and additional".

Our response

Done.

64. Cited from the referee's report

19. Line 18, page 14. remove "modelling unknown corrections to the AVISO velocity field". It has already been mentioned.

Our response

Done.

65. Cited from the referee's report

20. Line 19, page 14. Add "Finite Size Lyapunov Exponents" after "Finite Time Lyapunov Exponents"

Our response

Done. See please our respond No.43.

Statistical analysis of Lagrangian transport of subtropical waters in the Japan Sea based on AVISO altimetry data

S. V. Prants, M. V. Budyansky, and M. Yu. Uleysky

Laboratory of Nonlinear Dynamical Systems, Pacific Oceanological Institute of the Russian Academy of Sciences, 43 Baltiyskaya st., 690041 Vladivostok, Russia, URL: http://dynalab.poi.dvo.ru

Correspondence to: S.V. Prants
(prants@poi.dvo.ru)

Abstract. Northward near-surface Lagrangian transport of subtropical waters in the Japan Sea frontal zone is simulated and analyzed based on altimeter data for the period from January 2, 1993 to June 15, 2015. Computing different Lagrangian indicators for a large number of synthetic tracers launched weekly for 21 years in the southern part of the Sea, we find preferred transport pathways across the Subpolar Front. This cross-frontal transport is statistically shown to be meridionally inhomogeneous with "gates" and "barriers" whose locations are determined by the local advection velocity field. The gates "open" due to suitable dispositions of mesoscale eddies facilitating propagation of subtropical waters to the north. It is documented for the western, central and eastern gates with the help of different kinds of Lagrangian maps and verified by some tracks of available drifters. The transport through the gates occurs by a portion-like manner, i.e., subtropical tracers pass the gates in specific places and during specific time intervals. There are some "forbidden" zones in the frontal area where the northward transport has not been observed during all the observation period. They exist due to long-term peculiarities of the advection velocity field~~there~~.

1 Introduction

The Japan Sea (JS) is a mid-latitude marginal sea with dimensions of 1600×900 km, the maximal depth of 3.72 km and the mean depth of about 1.5 km. It spans regimes from subarctic to subtropical and is characterized by many of the same phenomena found in the deep ocean: fronts, eddies, currents and streamers, deep water formation, convection and subduction. It communicates with the Pacific Ocean at the south and east through the Tsushima/Korean and Tsugaru straits, respectively. In the north it is connected with the Okhotsk Sea through the Soya (La Perouse) and Tatarsky straits. All the four channels are shallow with depths not exceeding 135 m.

Bathymetry of the JS and its geographic and oceanographic features are shown in Fig. 1S in Supplementary material.

Warm and saline Pacific waters enter the Tsushima Strait and splits into three currents~~(Fig. 1)~~. Figure 1 with the AVISO velocity field, averaged for the period from January 2, 1993 to June 15, 2015, reflects the main known features of mesoscale near-surface circulation in the JS (Lee and Niiler, 2005; Lee and Niiler, 2006; Lee and Niiler, 2006; Lee and Niiler, 2009; Lee and Niiler, 2 The Nearshore Branch of the Tsushima Current flows northward along the western coast of the Honshu Island (Japan). Its Offshore Branch with a meander-like path flows into the Yamato Basin. The East Korean Warm Current flows northward along the eastern coast of Korea to meet the North Korean Cold Current which is a prolongation of the Liman Cold Current flowing southward along the Siberian coast down to Vladivostok. One of the major large-scale feature in the northern JS is a cyclonic gyre over the Japan Basin and the Tatarsky Strait. Some ~~aspects of the surface circulation in the JS have been studied by Hirose et al. (2005); Lee and Niiler (2005); Danchenkov et al. (2006); Talley et al. (2006); Yoon and Kim (2009); Kim and Yoon (2010); I~~ well known persistent mesoscale eddy-like features are also reproduced in Fig. 1. In the Ulleung Basin there are the warm Ulleung anticyclonic circulation (Chang et al., 2004; Mitchell et al., 2005; Shin, 2009; Lee and Niiler, 2010) with the center at about 37° N, 130.5° E and a cyclonic circulation around 36.7° N, 132° E called often as the cold Dok eddy (Lee and Niiler, 2010). The flow over bottom topography around the Oki Spur in the south-eastern part of the Sea generates the anticyclonic Oki Eddy (37.5° N, 134.2° E) (Isoda, 1994). In the western part of the Sea meandering of the East Korean Warm Current produces an anticyclonic circulation called as the anticyclonic Wonsan Eddy (39° N, 129° E) (Lee and Niiler, 2005).

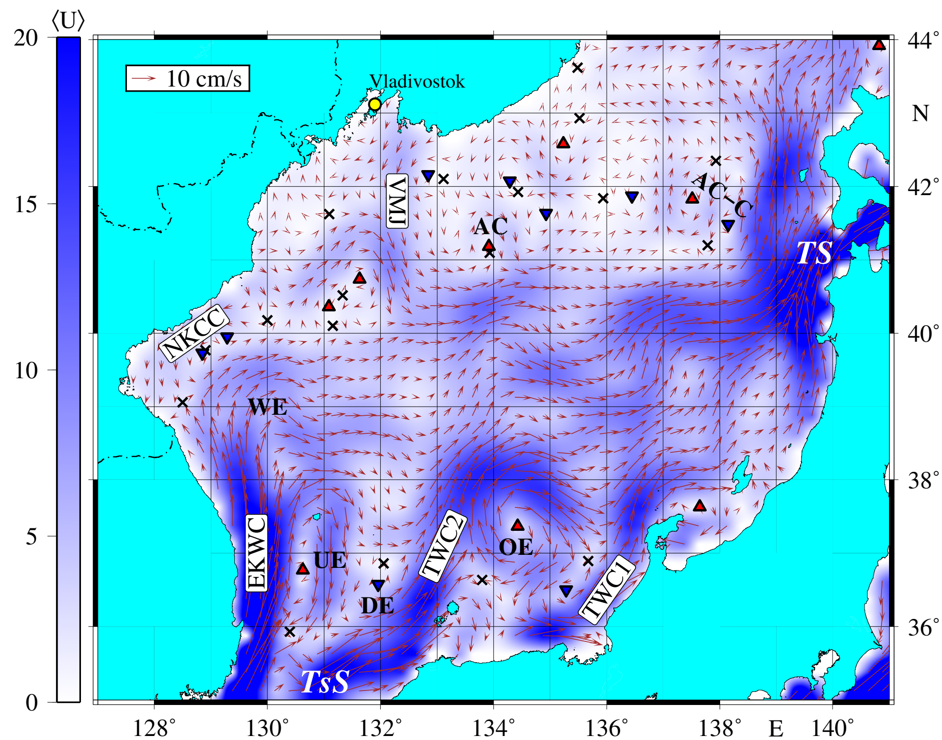

Figure 1. The AVISO velocity field averaged for the period from January 2, 1993 to June 15, 2015. Elliptic and hyperbolic stagnation points with zero mean velocity are indicated by triangles and crosses, respectively. Abbreviations: TsS (Tsushima or Korean Strait), TS (Tsugaru Strait), EKWC (East Korean Warm Current), NKCC (North Korean Cold Current), TWC1 and TWC2 (the first and second branches of the Tsushima Warm Current, UE (Ulleung eddy), DE (Dok eddy), OE (Oki eddy), WE (Wonsan eddy), AC-C (vortex pair near the eastern gate), AC (anticyclonic eddy over the Japan Basin), VMJ (Vladivostok meridional jet).

The confluence of northward warm subtropical waters with southward cold subarctic ones forms one of the most remarkable features in the ~~Sea~~sea, the distinct ~~SF~~ Subpolar Front that extends across the basin near 40° N (Park et al., 2004; Talley et al., 2006). It is a boundary of physical and chemical properties such as temperature, salinity, dissolved oxygen and nutrients. Like many other hydrological fronts, the ~~SF~~ Subpolar Front is a highly productive zone with favorable fishery conditions. It is not a continuous curve crossing the basin with a maximal thermal gradient. It is rather a vast area between $38°$ N and $41°$ N extending across the basin from the Korea coast to the Japanese islands.

Understanding transport pathways of subtropical water in the JS is relevant to a number of applications. Physical properties (temperature and salinity), chemical properties, pollutants and biota (phytoplankton, zooplankton, larvae, etc.) are transported and mixed by currents and eddies. Transport of heat to the north is crucial for climatic applications. The ability to simulate transport adequately would be useful to deal with the aftermath of accidents at sea such as discharges of radionuclides, pollutants and oil spills. It is also crucial, for instance, for understanding transport pathways for species invasions.

Since the last decades in the twentieth century, invasions of heat-loving fish (conger eel, tuna, moonfish and triggerfish) and some tropical and subtropical marine organisms (turtles, sharks and others) have been observed in the northern part of the Sea, ~~to~~ near the coast of Russia (Ivankova and Samuilov, 1979). It is natural to assume that such invasions could be caused by intrusions of subtropical waters in the northern part of the ~~Sea across the SF~~sea across the Subpolar Front. They may be also one of the reasons for a prolongation of the warm period in the fall in Primorye province in Russia since the 1990s (Nikitin et al., 2002). From the oceanographic point of view, this transport of subtropical waters contradicts long-held beliefs on circulation in the JS. It is believed that the ~~SF~~ Subpolar Front is a transport barrier for propagation of subtropical waters ~~across it~~ to the north, at least, in the western and central parts of the front area (see, e.g., Danchenkov et al., 2006). In this paper we use ~~the~~ altimetry data to simulate and analyze the northward near-surface transport of subtropical waters across the frontal area from January 2, 1993 to June 15, 2015.

The paper is organized as follows. Section 2 introduces briefly the altimetry data and simulation methods we use. Northward transport of subtropical waters across the ~~SF~~ frontal area is studied statistically in Sec. 3 ~~based on the altimetry data~~ for a long period of time. We compute, document and discuss preferred transport pathways and meridional distributions of artificial tracers launched in the southern part of the ~~Sea. A summary of the main results obtained is presented in Sec. 4. Supplementary data , associated with this article,~~ sea. Supplementary data can be found in the on-line version.

2 Data and methods

Geostrophic velocities were obtained from the AVISO database (http://aviso.altimetry.fr) archived daily on a $1/4° \times 1/4°$ grid from January 2, 1993 to June 15, 2015. Our Lagrangian approach is based on solving equations of motion for a large number of passive synthetic particles (tracers) advected by the AVISO velocity field

$$\frac{d\lambda}{dt} = u(\lambda, \varphi, t), \qquad \frac{d\varphi}{dt} = v(\lambda, \varphi, t), \tag{1}$$

where u and v are angular zonal and meridional velocities, φ and λ are latitude and longitude, respectively. Bicubical spatial interpolation and third order Lagrangian polynomials in time are used to provide numerical results. Lagrangian trajectories are computed by integrating the equations (1) with a fourth-order Runge-Kutta scheme with an integration step to be $1/1000$ day.

~~Lagrangian analysis of transport and mixing in marginal seas and in the deep ocean has experienced intense developments in the last decade (Harrison and Glatzmaier, 2012; Huhn et al., 2012; Prants et al., 2011b; Hernández-Carrasco et al., 2011; Keating et al., 2011;~~

The merged TOPEX/POSEIDON and ERS-1/2 altimeter data sets have been shown by Choi et al. (2004) to be appropriate to study mesoscale surface ~~ocean~~ circulation in the JS because of their comparatively small temporal and spatial sampling intervals. In particular, they have been shown to correlate well (0.95) with tide gauge data in the western JS (Choi et al., 2004). ~~We would like to stress that the AVISO velocity field, averaged for the period from January 2, 1993 to June 15, 2015 and shown in Fig. 1, demonstrates all the known mesoscale features of near surface circulation in the Sea including even correct locations of Ulleung, Dok, Oki and Wonsan quasi-permanent mesoscale eddies.~~

~~However, altimetry data provide the velocity field which is a geostrophical approximation to the real near-surface velocities. The results of our altimetry-based Lagrangian statistical analysis are expected to be valid on a mesoscale where the AVISO field may be considered to be a good approximation. Altimetry-based results should be considered with a caution when dealing with submesoscale structures (Keating et al., 2011). Local submesoscale phenomena like frontogenesis and ageostrophic instabilities cannot be reproduced correctly in altimetry-based velocity fields.~~

~~Transport of tracers is simulated for a comparatively long period of time, up to two years, and our results are based not on individual trajectories but on statistics for hundreds of thousands of trajectories. We cannot, of course, guarantee that we compute "true" trajectories for individual tracers in a chaotic velocity field. However, the description of general pattern of transport for thousands of tracers is much more robust. The shadowing lemma (see, e.g., Ott, 2002) states that although a numerically computed chaotic trajectory diverges exponentially from the "true" trajectory with the same initial conditions, there exists "a true" trajectory with a slightly different initial condition that stays near the numerically computed one. In other words, nobody is able to reproduce motion of a single passive particle in a chaotic flow, but it is possible to reproduce transport of statistically significant number of particles.~~

We study northward transport of tracers in the central part of the JS basin between 37° N and 42° N. With this aim 10^5 tracers have been launched weekly from January 2, 1993 to June 15, 2013 at the latitude 37° N from 129° E to 138° E. Trajectory of each tracer has been computed for two years after its launch date. We fixed the location and the moment of time where and when each tracer crossed a given latitude in the central JS between 37° N and 43° N. We ~~fix only the first crossing of a given zonal line. We~~ take into account the first ~~passage~~ crossing only, because we are interested not in a net transport but in the northward transport~~only~~. We stop to compute trajectories of those tracers which get into an AVISO cell with at least two corners situated at the land.

Each water parcel can be attributed to temperature, salinity, density and other properties which characterize this volume as it moves. In addition, each water parcel can be attributed to more specific characteristics which are trajectory's functions called "Lagrangian indicators". They are, for example, a distance passed by a fluid particle, its displacement from an original position, its travel time and others. The Lagrangian indicators contain information about the origin, history and fate of the corresponding water masses. Lagrangian maps are plots of Lagrangian indicators versus particle's initial positions. A studied area is seeded with a large number of tracers whose trajectories are computed for a given period of time to get the field of a specific Lagrangian indicator whose values are coded by color and represented as a map in geographic coordinates.

To simulate and analyze transport across the frontal area, we ~~propose a Lagrangian methodology with a complex of the numerical codes compiled to compute a number of Lagrangian indicators for synthetic tracers and plot~~ solve successively a few tasks which are numbered in the text in accordance with the following diagrams and Lagrangian maps.

1) ~~Meridional~~ A meridional distribution of the number of tracers, N, crossing fixed latitudes, λ_f, in the central JS with a space step $0.1°$. The corresponding data are represented as a density map which shows by color the density of tracks of the ~~tracers~~ particles crossed all the latitudes in the central JS from January 2, 1993 to June 15, 2015. Tracking maps show where the subtropical tracers, which crossed eventually the fixed zonal line through fixed meridional "gates", wandered for the whole integration period. They also can be represented as a $N(\lambda_f)$ distribution which shows how many tracers reached a fixed zonal line at the longitude λ_f for the whole period of integration.

2) Fixing initial longitudes λ_0 of launched tracers along the material line 37° N, we compute those final longitudes λ_f at which they cross a fixed zonal line for the whole period of integration. The results are represented as $\lambda_0 - \lambda_f$ plots.

3) The $T - \lambda_f$ plots show when and at which longitudes the tracers, launched at 37° N, crossed the latitudes 40° N and 42° N for the whole period of integration.

4) In order to document and visualize intrusions of subtropical waters into subarctic ones~~we compute so-called Lagrangian maps by integrating the advection equations (1) backward in time~~ , we compute backward-in time Lagrangian maps (Prants, 2015). A subbasin in the ~~Sea~~ sea is seeded at a fixed date with a large number of tracers whose trajectories are computed backward in time for a given period of time. We use three kinds of the Lagrangian maps in this paper. Such maps have been shown to be useful in studying large-scale transport and mixing in various basins, from bays (Prants et al., 2013) and seas (Prants et al., 2011a, 2013) to the ocean scale (Prants et al., 2011b; Prants, 2013), in quantifying propagation of radionuclides in the Northern Pacific after the accident at the Fukushima Nuclear Power Plant (Prants et al., 2011b, 2014a; Prants, 2014; Budyansky et al., 2015) and in finding potential fishing grounds (Prants et al., 2014b, c).

In order to track those subtropical waters which were able to cross the ~~SF and reach given latitudes in the northern JS, we mark by~~ Subpolar Front and reach northern latitudes, we color the tracers that reached the line 37° N in the past and compute how much time it took. In order to know where this or that tracer came from for a given period of time, we compute the drift maps with boundaries. The waters, that entered a given area through its southern boundary, are shown by one color~~on such a map~~, and the waters, that came through the northern boundary, are shown by another color. ~~With another kind of maps, drift maps , we compute~~ The drift maps show by nuances of the grey color the finite-time displacement of tracers, D, that is a distance between ~~the~~ final, (λ_f, φ_f), and initial, (λ_0, φ_0), positions of advected particles on the Earth sphere ~~.~~ with the radius R_E

$$D \equiv R_E \arccos[\sin\varphi_0 \sin\varphi_f + \cos\varphi_0 \cos\varphi_f \cos(\lambda_f - \lambda_0)]. \tag{2}$$

"Instantaneous" stagnation elliptic and hyperbolic points are indicated ~~on the Lagrangian maps~~ by triangles and crosses, respectively. They are points with zero velocity which are computed daily. Up(down)ward orientation of one of the triangle's top means anticyclonic (cyclonic) rotations of water around them. The triangles are colored as red (blue) marking elliptic points for anticyclones (cyclones). The elliptic points, situated mainly in the centers of eddies, are those stagnation points around which the motion is stable and circular. The hyperbolic points, situated mainly between and around eddies, are unstable ones with the directions along which waters converge to such a point and another directions along which they diverge. The stagnation points are moving Eulerian features and may undergo bifurcations in the course of time. In spite of nonstationarity of the velocity field some of them may exist for weeks and much more.

We have used for a comparison and verification tracks of surface drifters that are available at the site http://aoml.noaa.gov/phod/dac.

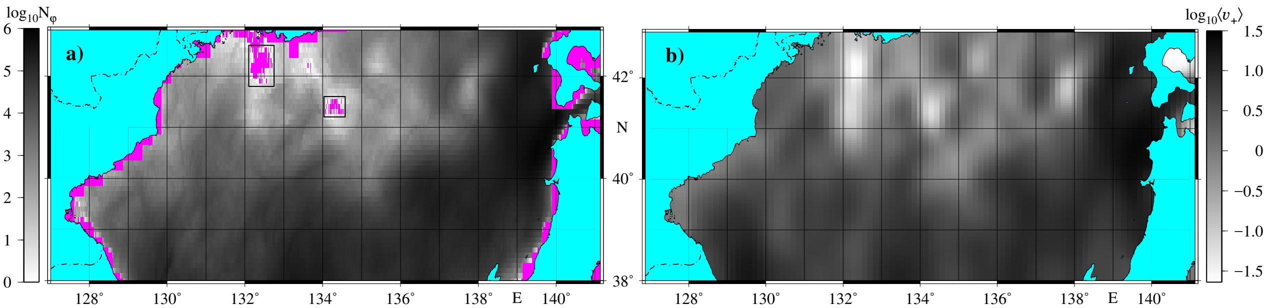

Figure 2. a) The logarithmic-scale density of tracks of the tracers crossing all the latitudes φ in the central JS, N_φ, from January 2, 1993 to June 15, 2015. The rectangular magenta areas are forbidden zones where the northward transport has not been observed during the whole integration period. The ~~other~~ magenta areas near the ~~cost~~ coast mean that the AVISO grid cells there touch the land, and we did not compute trajectories there. The tracers have been launched weekly along the zonal line at 37° N from January 2, 1993 to June 15, 2013. b) Distribution of the averaged northward component of the AVISO velocity field $\langle v_+(\lambda,\varphi)\rangle$ in the logarithmic-scale averaged over the same period.

3 Results and Discussion

3.1 Northward transport of subtropical water and advection velocity field

~~Figure 1 with the AVISO velocity field, averaged for the period from January 2, 1993 to June 15, 2015, reflects the known features of mesoscale near-surface circulation in the central JS. The Tsushima Warm Current splits into three parts. The first one (TWC1 in Fig. 1) is the near shore branch flowing northward along the western coast of the Honshu Island (Japan). The second one (TWC2) is the offshore meander-like branch, and the third one is the East Korean Warm Current flowing northward as a western boundary current along the eastern coast of the Korean peninsula (EKWC). It encounters the North Korean Cold Current flowing southward (NKCC). Both the currents separate from the Korean coast at about and flow to the east forming the SF.~~

~~Some well known quasi-stationary mesoscale eddy-like features are also visible in Fig. 1. In the Ulleung Basin there are the warm Ulleung anticyclonic circulation (Shin et al., 2005; Mitchell et al., 2005; Shin, 2009; Lee and Niiler, 2010) with the~~

~~center at about , (UE) and a cyclonic circulation called often as the cold Dok eddy (DE) (Lee and Niiler, 2010) with the center at about , . The flow over bottom topography around the Oki Spur in the south-eastern part of the Sea generates the anticyclonic Oki Eddy (OE) with the center at about , (Isoda, 1994). In the western part of the Sea meandering of the East Korean Warm Current produces an anticyclonic circulation called as the anticyclonic Wonsan Eddy (WE) with the center at about , (Lee and Niiler, 2005).~~

Plot in Fig. 2a shows the density of tracks of tracers launched along 37° N and crossed all the latitudes in the central JS for the whole period of integration~~, from January 2, 1993 to June 15, 2015.~~. The density is coded by nuances of the grey color in the logarithmic scale, $\log_{10} N_\varphi$. The magenta areas in Fig. 2a along the coastal line mean that the AVISO grid cells there touch the land, and we did not compute trajectories there. Uneven density of points in Fig. 2a means that the northward transport of subtropical waters is meridionally inhomogeneous with ~~a kind of~~ "gates" with increased density of points. The gates are such spatial intervals along a given zonal line across which subtropical tracers prefer to cross it.

Any tracer, as a passive particle, is able to cross the fixed latitude in the northward direction if the northward component of the velocity field is nonzero at its location. In Fig. 2b we plot distribution of the northward component of the AVISO velocity field averaged over the whole period of integration as follows:

$$\langle v_+(\lambda,\varphi)\rangle = \frac{1}{\mathbf{n}}\sum \theta(v(\lambda,\varphi))v(\lambda,\varphi), \tag{3}$$

where $v_+(\lambda,\varphi)$ is a northward (positive) component of the velocity at the point (λ,φ), $\theta(v)$ the Heaviside function and $\mathbf{n}$ the number of days in the period from January 2, 1993 to June 15, 2015. Comparing Lagrangian representation in Fig. 2a with the Eulerian one in Fig. 2b, it is clear that areas with increased density of points in Fig. 2a ~~correlates~~ correlate well with areas with increased average values of the northward component of the AVISO velocity field in Fig. 2b.

Thus, the northward transport of subtropical waters in the central JS is determined mainly by the local advection velocity field, more precisely by local values of ~~the northward componentof the velocity~~its northward component. The greater is ~~the northward component of the velocity~~ that northward component at a given point and the longer is the period of time when it is positive the more tracers are able to cross the corresponding latitude.

The density difference in some meridional ranges in Fig. 2a may be very large because of the logarithmic-scale representation. There are even some places in the northern ~~SF~~ frontal area where the northward transport has not been observed during all the simulation period, from 1993 to 2015. They are marked by magenta rectangles in Fig. 2a. One "forbidden" zone is situated in the deep Japan Basin with the center at about 41.5° N, 134.2° E, and another one is situated to the south off Vladivostok from 43° N to 41° N approximately along the 132° E meridian. We stress that they are forbidden only to northward transport of tracers but can be and really are open to transport in other directions.

The "forbidden" zones exist due to long-term peculiarities of the advection velocity field there. The zone to the south off Vladivostok exists due to a quasi-permanent southward jet approximately along the meridian 132° E from 43° N to 40° N (VMJ in Fig. 1). It turns to the east at about 40° N and contributes to the eastward transport. In fact, the northward velocity is practically zero in this area (see Fig. 2b) and, therefore, the northward transport is absent. The other "forbidden" zone exists due to two factors, the presence of a quasi-permanent anticyclonic eddy with the center at about 41.3° N, 134° E in the deep

Japan Basin (AC in Fig. 1) and the eastward zonal jet blocking northward transport across it. Topographically constrained anticyclonic eddies with the center at about 41° N – 41.5° N, 134° E – 134.5° E have been regularly observed there (Takematsu et al., 1999; Talley et al., 2006; Prants et al., 2015).

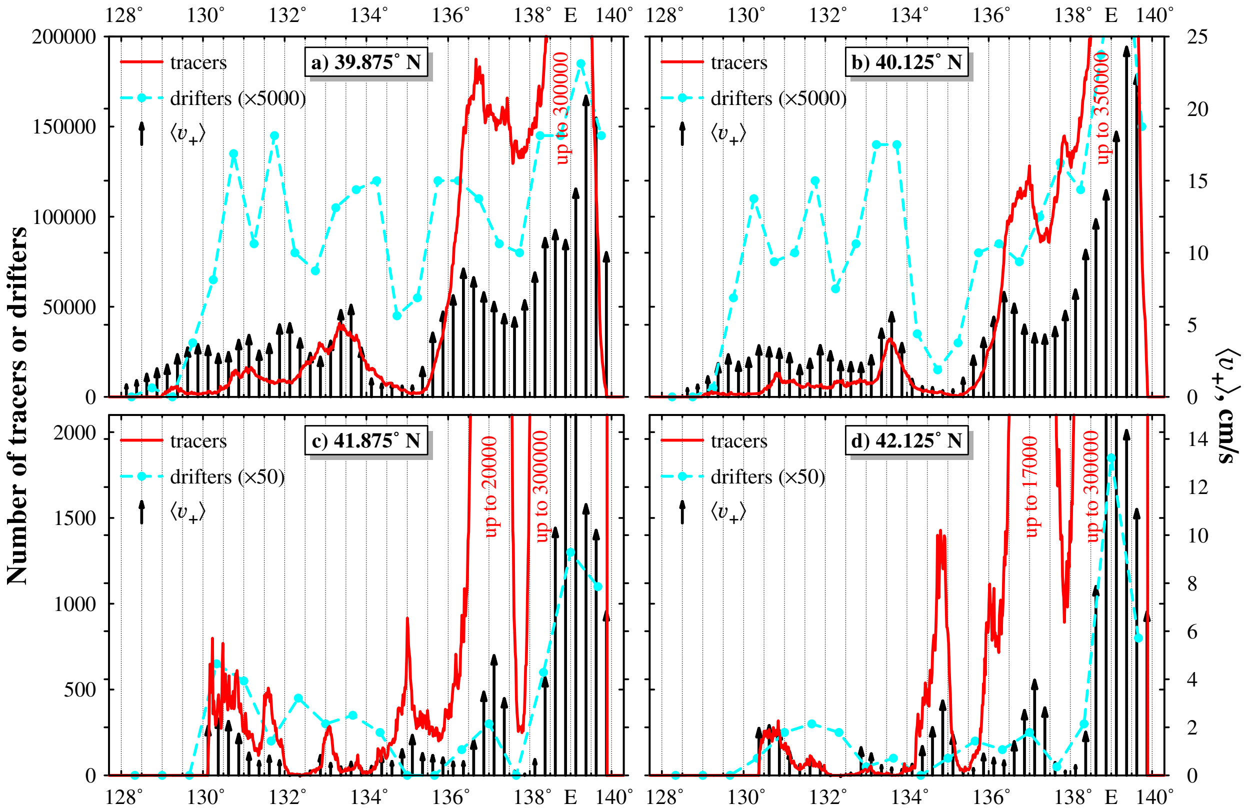

Figure 3. Meridional distributions of the number of tracers which crossed indicated zonal lines (solid curves), of the averaged northward component of the AVISO velocity in cm s^{-1} (arrows) and of the number of crossings of those zonal lines by available drifters (dashed curves). The period of observation is from January 2, 1993 to June 15, 2015.

3.2 Transport pathways of subtropical water and its intrusions across the Subpolar Front

Now let's look more carefully at the meridional distribution of subtropical tracers crossed the ~~SF~~ Subpolar Front for the whole period of simulation. We choose for reference four zonal lines along the AVISO grid at 42.125° N, ~~;~~ 41.875° N, ~~;~~ 40.125° N ~~, and at~~ and 39.875° N~~, . These distributions~~ . They are shown in Fig. 3 ~~for each zonal line~~ by solid curves with superimposed meridional distributions of the averaged northward AVISO velocity (arrows). The ~~numbers~~ number of crossings of those latitudes by available ~~drifters are~~ 333 drifters is shown by dashed curves. The correspondence between the peaks in

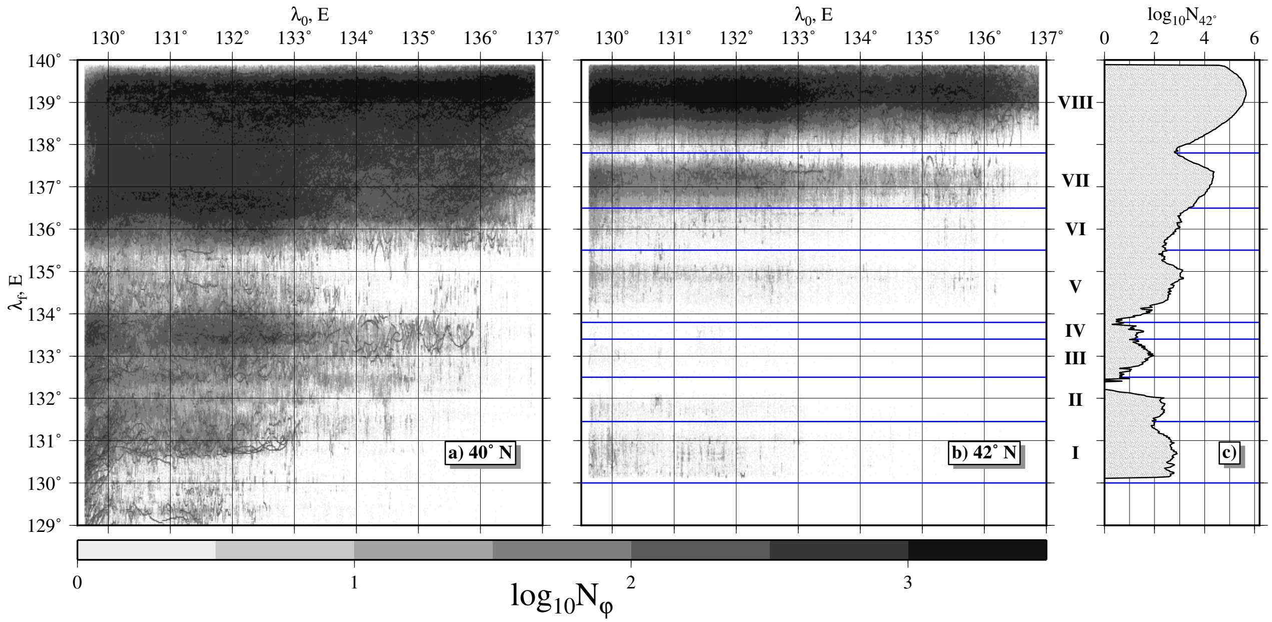

Figure 4. Density plots show in the logarithmic scale how many and at which final longitudes λ_f the tracers with initial longitudes λ_0, were able to cross the zonal lines a) 40° N and b) 42° N for the whole simulation period. The tracers have been launched weekly at the line 37° N from January 2, 1993 to June 15, 2013. c) Meridional distribution of the number of tracers which crossed the zonal line 42° N for the whole simulation period. This line is divided in eight intervals numbered by the roman numerals.

the meridional distributions of the tracers~~and of~~, drifters and the averaged northward AVISO velocity is rather good for all the chosen zonal lines confirming their direct connection.

~~The tracer's peaks correlate more or less with the number of crossings of the chosen zonal lines by drifters. The correlation is rather good for the western and eastern parts but not for the central one. The~~ However, the comparison with drifters should be taken with care because of a comparatively small number of available drifters~~especially in the central part of the SF. Moreover, the drifters~~. Drifters, are not ideal passive tracers~~and they, of course,~~, and their motion is subjected to submesoscale features which were not caught by altimetry-derived data. Moreover, the drifters have not been launched at the zonal line 37° N like artificial tracers in simulation. Their launch sites for more than 20 years have been distributed rather randomly over the basin.

~~The meridional tracer distribution in Fig. 3 allows to distinguish the eastern, central and western gates in the central JS which strongly differ by the number of passing tracers~~

The local maxima and minima of the distribution functions correspond to gates and conditional barriers, respectively. The very eastern, 138° E–140° E, and western, 129° E–131° E, gates are provided mainly by the near shore branch of the Tsushima Warm Current and the East Korean Warm Current, respectively. The central gate, 133° E–137° E, exists, probably, due to topographically constrained features over the Yamato Rise there (see Fig. 1S in Supplementary material). The transport through that gate will be shown to be enhanced due to a specific disposition of ~~SF~~ frontal eddies regularly observed there. The intervals between the gates may be called “conditioned barriers” because of a comparatively small number of tracers crossing zonal lines there, and because they used to “open” for a comparatively short time intervals.

Figures 4a and b show in accordance with the task 2 at which final longitudes λ_f the tracers, launched with the initial longitudes λ_0 at the line 37° N, reached the zonal lines 40° N and 42° N for the whole period of integration. Meridional distribution of the number of tracers with pronounced peaks which crossed the zonal line 42° N for the same period is plotted in Fig. 4c. This zonal line was divided in eight meridional intervals numbered by the roman numerals in Figs. 4b and c with the horizontal straight lines running via local minima at the distribution in Fig. 4c.

The Tsushima Warm Current contributes mainly to the eastern peak VIII at the distribution in Fig. 4c. The black color across all the range of initial longitudes λ_0 in Fig. 4b means that fluid particles, crossing eventually the line 42° N through the gate 138° E – 140° E, could have any value of the initial longitude λ_0 at the zonal line 37° N. They could reach that gate by different ways: either to be initially trapped by the near shore branch or to be advected by the offshore branch and then to enter the near shore branch. Moreover, those particles could be involved initially in the East Korean Warm Current and then be transported to the east along the ~~SF~~ Subpolar Front and eventually join to the Tsushima Warm Current. Thus, the subtropical tracers, crossing the gate VIII, may have rather distinct values of some Lagrangian indicators, e.g., travelling time and distance passed.

There is a narrow barrier, the white strip in Fig. 4b between the gates VIII and VII, with the center at the local minimum at 137.8° E in Fig. 4c. A comparatively small number of tracers have been able to cross the line 42° N there for the whole simulation period. The gate VII between 136° E and 137.8° E (Figs. 4b and c) provides northward transport of subtropical tracers by means of a quasi-permanent vortex pair located there. The number of subtropical tracers passing through this gate is much smaller than that passing through the gate VIII (remember the logarithmic scale in Fig. 4). Only a small number of tracers, launched initially at the very eastern part of the zonal line 37° N, were able to cross the line 42° N through that gate, because most of the eastern tracers passed through the gate VIII to be captured by the near shore branch of the Tsushima Warm Current. Most of the tracers, passing through the gate VII, came from the western and central parts of the material line at 37° N. The number of subtropical tracers, passing through the central and western gates, are much smaller as compared with those passed the eastern ones. We distinguish two central gates V and III, 134° E – 135.5° E and 132.5° E – 133.5° E, respectively, and the western gates I and II (Fig. 4c) in the range 130° E – 132.5° E. It follows from Fig. 4b that the western and central gates collect subtropical tracers mainly from the western part of the initial zonal line, from 129° E to 133° E. In other words, water parcels from its eastern part (133° E – 137° E) practically do not pass through those gates at the latitude 42° N. Thus, the western part of the initial material line at 37° N contributes to all the peaks at the tracer distribution 42° N, whereas its eastern part contributes mainly to the Tsushima peak.

To visualize the transport paths by which subtropical tracers reach the northern ~~SF~~ frontal area we compute so-called tracking maps in Fig. 4S in Supplementary material showing where the subtropical tracers, which crossed eventually the zonal line 42° N, wandered for the whole integration period.

The $T - \lambda_f$ plots in Figs. 2S and 3S in Supplementary material show when and at which longitudes the tracers, launched weekly at the zonal line 37° N from January 2, 1993 to June 15, 2013, reached the zonal lines 40° N and 42° N, respectively. It is declared in Sec. 2 as the task 3. As an example, we show in Fig. 5 a typical $T - \lambda_f$ plot for the tracers crossed eventually

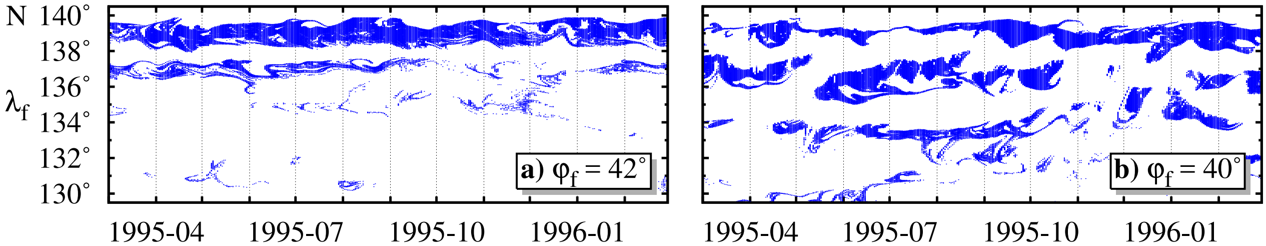

Figure 5. The $T-\lambda_f$ plots show when and at which longitudes the tracers, launched at the zonal line 37° N, crossed eventually the zonal lines a) 40° N and b) 42° N in the period from March 1, 1995 to March 1, 1996.

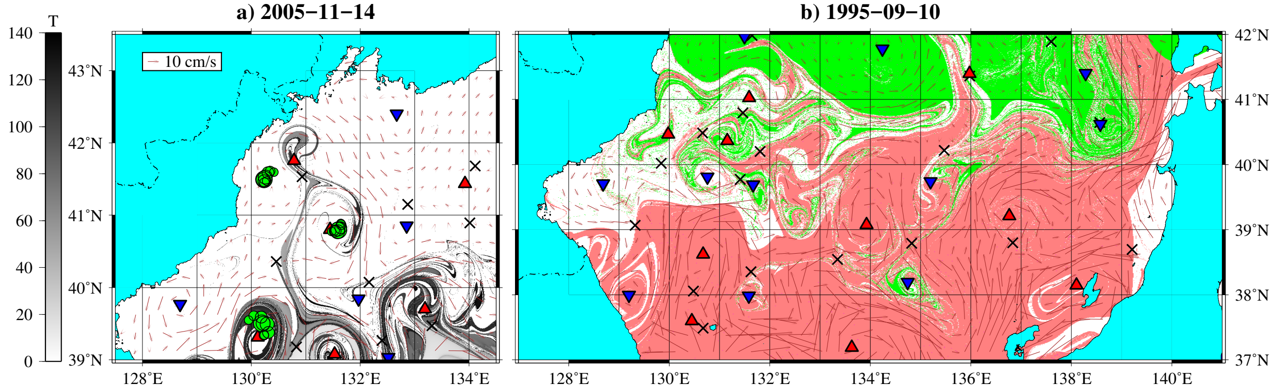

Figure 6. a) The Lagrangian map documents intrusions of subtropical water to the southern coast of Russia through the western gate. Nuances of the grey color code travelling time T in days that took for subtropical tracers to reach their locations on the map from the latitude 37° N to the dates shown. "White" tracers are those ones which did not come from the latitude 37° N for the integration period, 140 days. Locations of available drifters are shown by full circles for one day before and after the dates indicated. b) The drift map documents a streamer-like northward transport of subtropical water across the front through a central gate with the help of the cyclone with the center at 41.5° N, 134.4° E. The ~~AVISO velocity field is shown by arrows. "Instantaneous" elliptic and hyperbolic points, to be present in the area on a fixed day, are indicated by triangles and crosses, respectively. The~~ red and green colors code the waters that entered the studied area for two years through its southern and northern boundaries, respectively. White color marks the tracers getting the coast.

the zonal lines 40° N and 42° N in the period from March 1, 1995 to March 1, 1996. It demonstrates the eastern gates VIII and VII (Fig. 4) through which the subtropical tracers cross the corresponding latitudes. The locations of the central and western gates fluctuate in time, and some gates may be even closed for a while to the northward transport. The patchiness in the plot means that subtropical tracers prefer to cross the zonal lines in the specific places (note the peaks in Figs. 3) and during specific time intervals. Any patch with a large number of tracers somewhere, ~~say~~for example, at the central meridional gate means that a water mass proportional to the size of this patch passed through the central gate across a given latitude during the period of time proportional to its zonal size. Thus, the northward transport of subtropical water across the ~~SF~~ Subpolar Front occurs

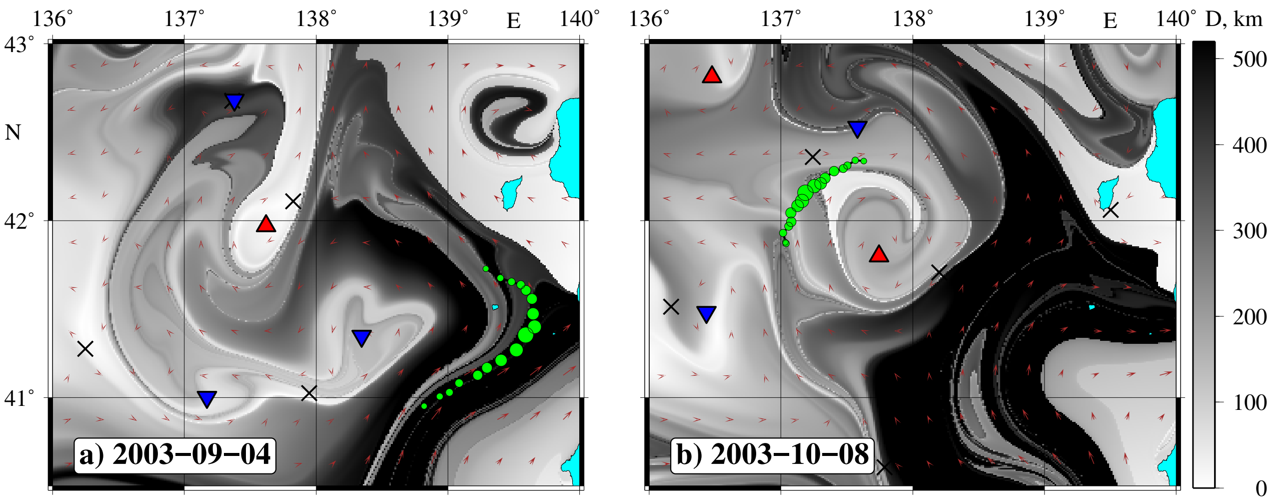

Figure 7. The drift maps with snapshots of the drifter's track superimposed show how the vortex pair facilitates transport of subtropical tracers to the northwest through the eastern gate. The displacement of particles D in km, computed for a two months backward in time from the day indicated in each panel, are coded by shades of the grey color. Locations of the drifter No. 35660 are shown by full circles for two days before and after the day indicated.

by a portion-like manner. Specific oceanographic conditions may arise in a given area and at a given time which produce a large-scale intrusion of subtropical water to the north by means of mesoscale eddies to be present there.

~~One of the motivations of our work was an explanation of invasion of tropical and subtropical marine organisms in the northern part of the Sea, to the southern coast of Russia (Ivankova and Samuilov, 1979).~~

To document an intrusion of subtropical water there, we compute the backward-in-time Lagrangian maps (for a recent review of backward-in-time techniques see Prants, 2015). It is a realization of the task 4 in Sec. 2. The basin, shown in Fig. 6a, is seeded with a large number of tracers for each of which we compute the time required for a tracer to reach its location on the map to a fixed date from the latitude 37° N. It is a kind of so-called residence-time maps (Lipphardt et al., 2006; Uleysky et al., 2007; Hernández-Car The travelling time T in days is coded by nuances of the grey color.

The map in Fig. 6a illustrates a mechanism of the penetration of subtropical water to the north through the western gate. A vortex street with four anticyclones has been formed in the fall of 2005 to the north of the ~~SF~~ Subpolar Front in the western part of the ~~Sea~~sea. Their centers are marked in Fig. 6a by the elliptic points (triangles) with the coordinates 39.1° N, 131.5° E; 39.3° N, 130.1° E; 40.8° N, 131.4° E and 41.7° N, 130.8° E. Subtropical "grey" tracers propagate along the unstable manifolds of the three hyperbolic points between and around of those eddies to the north (simple description of the notion of stable and unstable manifolds in fluid flows can be found, e.g., in Prants, 2014). The hyperbolic points are marked by crosses in Fig. 6a with the coordinates 39.2° N, 130.8° E; 40.3° N, 130.5° E and 41.6° N, 130.9° E. Thus, the vortex street provides an intrusion of subtropical water to the southern coast of Russia. The evidence of, at least, two anticyclones in the AVISO velocity field is confirmed by tracks of two available drifters~~()~~. Their locations are shown in Fig. 6a by full circles for one day before and after the date indicated on the map. The drifter No. 56739 has been trapped by the anticyclone with the center at $39.3°$ N, $130.1°$ E and the drifter No. 56746 — by the anticyclone with the center at $40.8°$ N, $131.4°$ E.

We have found ~~such~~ similar episodes with penetration of subtropical waters far to the north to the coast of Russia through the western gate in different years~~as well~~. Peripheries of mesoscale eddies in the ocean are known to be transport pathways for larvae, fish and other marine organisms (see, e.g., (Cotte et al., 2010; Prants, 2013; Prants et al., 2014c) and references therein). In our case they might be a kind of transport for heat-loving organisms to reach the southern coast of Russia (Ivankova and Samuilov, 1979).

An example of the intrusion of subtropical water through the central gate across the ~~SF~~ Subpolar Front is shown in Fig. 6b with another kind of Lagrangian maps, so-called backward-in-time drift maps (Prants et al., 2011a, 2014a) computed as a part of the task 4. The red and green colors on backward-in-time drift maps code the waters that entered the studied area for two years through its southern and northern boundaries, respectively. In the beginning of September, 1995 a mesoscale cyclonic eddy to the north of the ~~SF~~ Subpolar Front with the center at about $41.5°$ N, $134.4°$ E "grabbed" some subtropical water at its southern periphery and pulled it to the north. ~~The red and green colors on backward-in-time drift maps code the waters that entered the studied area for two years through its southern and northern boundaries, respectively.~~ In the course of time the streamer-like intrusion of subtropical tracers reached the latitude $42°$ N moving to the north (Fig. 6b).

As to the transport of subtropical waters through the eastern gate VII (see Fig. 3 and Fig. 4), it occurs mainly due to existence of a quasi-permanent vortex pair labelled as AC-C in the mean field in Fig. 1. It provides a propulsion of some subtropical tracers to the northwest whereas most of them, propagating along the eastward frontal jet, join to the Tsushima Warm Current and flows out to the Pacific through the Tsugaru Strait. The maps in Supplementary material (Figs. 5S and 6S) document a typical situation with a propulsion of subtropical water to the northwest in September – October, 2003. The browsing and analysis of Lagrangian drift maps, computed for the whole observation period, have shown that frontal eddies used to facilitate the northward transport of subtropical water across the ~~SF~~ Subpolar Front via the central and eastern gates.

To illustrate how this quasi-permanent vortex pair works we show in Fig. 7 the drift map for tracers distributed over the area and advected for two months backward in time starting from the dates indicated. The values of displacements of the tracers, D, in km are coded by shades of the grey color. So, the black tracers have displaced for the same time considerably as compared to the white ones. To verify our simulation we show in Fig. 7 positions of the drifter No. 35660 by full circles for two days before and after the date indicated with their size increasing in time. The entire track of that drifter, launched on May 2, 2003 at the point $34.925°$ N, $129.3°$ E, is shown in Fig. 7S in Supplementary material.

In the beginning of September, 2003 (Fig. 7a) the vortex pair at the entrance to the gate VII consists of an anticyclone with the center at about $42°$ N, $137.7°$ E and a cyclone $41.25°$ N, $138.35°$ E. The cyclone winds some subtropical water from the eastward frontal jet round its northern periphery in a streamer-like manner (see the black tongue in Fig. 7a). Then this water is wound by the anticyclone round its southern periphery and is propulsed to the ~~northwest~~northeast. It is confirmed by snapshots of the track of the drifter No. 35660 for September – October, 2003 (see Fig. 6S in Supplementary material). Being in the beginning of September in the main stream (Fig. 7a), it has drifted round the cyclone for the first half of September, then round the anticyclone for the second half of September and in the beginning of October. Eventually the drifter No. 35660 crossed the latitude 42° N (Fig. 7b) and moved to the north lugged by modified subtropical waters.

3.3 Discussion of the effect of possible altimetry errors on statistical features of Lagrangian transport

It has been shown statistically ~~in this section~~ that the average northward component of the AVISO velocity field dictates preferred near-surface transport pathways of subtropical waters in the central JS. The ability of satellite altimetry to accurately measure sea level anomalies has vastly improved over the last decade. However, there are still some measurement errors due to different reasons that lead to errors in the velocity field provided by ~~the AVISOwe used~~AVISO.

~~Some simulation results with an imperfect AVISO velocity field can be verified by comparing them with satellite, drifter and in situobservations. It has been done in this paper when possible. The AVISO velocity field, averaged for the whole observation period (Fig. 1), reproduces all the known main mesoscopic features of near surface circulation in the Sea (Hirose et al., 2005; Lee and Niiler not only pathways of the main currents but even locations of Ulleung, Dok, Oki, Wonsan and other quasi-permanent mesoscale eddies (Fig. 1). Moreover, the simulation has been compared with available tracks of drifters (see Figs. 3, 6 and 7).~~

In this section we discuss possible effect of errors in the altimetry field on our simulation results. ~~Nobody knows, of course, "true" velocity field in the real ocean.~~ The AVISO velocity field has errors as compared with ~~an unknown~~ a "true" velocity field~~which can be considered as~~. The difference could be simulated by adding a noise $\Delta(u, v)$ in the velocity data. The question is how reliable are our statistical simulation results based on an imperfect AVISO velocity field? ~~To which extent one can trust to them?~~ All the simulation results, based on the average AVISO velocity as in Fig. 1, are supposed to be reliable because the errors are averaged out for 22 years. As to other simulation results, they depend on possible noise Δv in the AVISO northward component v_+ which could, in principle, change the results but only if the noise would be strong enough to change direction of the meridional velocity, i.e., if $\Delta v > |v|$. If the average AVISO northward component v_+ is large enough as in the areas with dominated northward currents, we don't expect that it would be changed there significantly under influence of noise. So, locations of the preferred transport pathways ~~in Figs. 3 and Fig. 4, which are dictated by that component,~~ are not expected to be changed significantly.

If the average AVISO northward component v_+ is small, then two options are possible.

1) It is small due to domination of a southward current somewhere, i.e., $v_- \gg \Delta v$. It is clear that possible noise has practically no effect on northward transport in this case. ~~Say~~For example, the forbidden zone in Fig. 2a to the south off Vladivostok, where northward transport has not been observed during the whole observation period, should be located there at any realistic level of noise because it exists due to domination of a sufficiently strong southward jet (VMJ in Fig. 1).

2) The average AVISO northward component v_+ is small due to a smallness of the absolute velocity, i.e., $\sqrt{u^2+v^2} \sim \Delta v$. In this case northward and southward transports are equalized, and they are small if the noise is small enough. It is hardly to expect such a situation along the ~~SF because of a plenty of~~ Subpolar Front because of the presence of numerous mesoscale eddies along the front where the absolute velocities are not small.

~~As to~~ The influence of possible errors in altimetry-derived velocity field on concrete mesoscale features ~~, it~~ has been studied by Harrison and Glatzmaier (2012); Hernández-Carrasco et al. (2011); Keating et al. (2011) by analyzing how an additional noise in the advection equations ~~, modelling unknown corrections to the AVISO velocity field,~~ might change Lagrangian coherent structures revealed by the finite-time ~~Lyapunov technique~~and finite-size Lyapunov techniques. Strongly attracting and repelling individual Lagrangian coherent structures in the California Current System have been shown to be robust to perturbations of the velocity field of over 20% of the maximal regional velocity (Harrison and Glatzmaier, 2012). Individual trajectories have been shown to be sensitive to small and moderate noisy variations in the velocity field but statistical characteristics and large-scale structures like mesoscale eddies and jets are not (Cotte et al., 2010; Hernández-Carrasco et al., 2011; Keating et al., 2011).

4 Conclusions

The main results of altimetry-based simulation and analysis of the northward near-surface Lagrangian transport of subtropical water across the Japan Sea frontal zone for the period from January 2, 1993 to June 15, 2015 are the following.

1. A methodology to simulate and analyze Lagrangian large-scale transport in frontal areas is developed (tasks 1–4 in Sec. 2).

2. There are “forbidden” zones in the Japan Sea where the northward transport has not been found during all the observation period (~~see~~ the rectangles in Fig. 2a). The “forbidden” zone to the south off Vladivostok exists due to a quasi-permanent southward jet there (~~see~~ VMJ in Fig. 1). The other “forbidden” zone exists due to the presence of a quasi-permanent topographically constrained anticyclonic eddy with the center at about 41.3° N, 134° E in the deep Japan Basin and the eastward zonal jet blocking northward transport there (~~see~~ AC in Fig. 1).

3. Northward near-surface Lagrangian transport of subtropical water across the Subpolar Front has been statistically shown to be meridionally inhomogeneous with specific gates and barriers in the frontal zone whose locations are determined by the local advection velocity field (~~see~~ the pronounced peaks in Figs. 3 and Fig. 4).

4. The transport through the gates has been shown to occur by a portion-like manner, i.e., those gates “open” during specific time intervals (~~see~~ a patchiness in Fig. 5 and Figs. 2S and 3S).

5. The gates “open” due to suitable dispositions of mesoscale frontal eddies facilitating propagation of subtropical waters to the north. It is documented for the western, central and eastern gates with the help of different kinds of Lagrangian maps and validated by some tracks of available drifters (~~see~~ the intrusions of subtropical tracers around the eddies in Figs. 6, 7, 5S and 6S). In particular, invasion of tropical and subtropical marine organisms in the northern part of the ~~Sea~~sea, to the southern coast of Russia, can be explained by the presence of vortex streets at the western gate (Fig. 6).

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Supplementary materials associated with this paper can be found in the on-line version.

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